NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

RAPID AIRLIFT PLANNING FOR AMPHIBIOUS-READY GROUPS

by

Travis A. Hartman

September 2015

Thesis Advisor:	Robert Dell
Co-Advisor:	Connor McLemore
Second Reader:	Gerald Brown

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2015	Master's Thesis

4. TITLE AND SUBTITLE
RAPID AIRLIFT PLANNING FOR AMPHIBIOUS-READY GROUPS

5. FUNDING NUMBERS

6. AUTHOR(S) Hartman, Travis A.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

An Amphibious Ready Group (ARG) consists of ships capable of conducting flight operations that routinely require the transport of personnel and cargo (PMC) to remain operationally viable. Planning PMC transport for an ARG and nearby airfields is labor intensive and often results in the inefficient use of rotary wing and tilt rotor aircraft. Personal experience shows that: (1) only a limited number of aircraft routes are explored; (2) operating costs are not explicitly considered; and (3) PMC plans may take up to 12 hours to create. This thesis develops and implements the PMC Route Optimizing Program (PROP), an optimization-based decision support system. PROP output prescriptions provide aircraft takeoff and landing times, routes, and transported PMC -- everything required for planning PMC missions. We demonstrate PROP using 18 realistic test cases with up to four aircraft, five pickup and delivery locations, and up to 500 PMC requests. All test cases solve in less than one hour.

14. SUBJECT TERMS
vehicle routing problem, vehicle synchronization, military airlift, passenger and cargo transport, helicopter routing

15. NUMBER OF PAGES
61

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

RAPID AIRLIFT PLANNING FOR AMPHIBIOUS-READY GROUPS

Travis A. Hartman
Lieutenant Commander, United States Navy
B.S., Purdue University, 1999

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 2015

Author: Travis A. Hartman

Approved by: Robert Dell
Thesis Advisor

Connor McLemore
Co-Advisor

Gerald Brown
Second Reader

Patricia Jacobs
Chair, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

An Amphibious Ready Group (ARG) consists of ships capable of conducting flight operations that routinely require the transport of personnel and cargo (PMC) to remain operationally viable. Planning PMC transport for an ARG and nearby airfields is labor intensive and often results in the inefficient use of rotary wing and tilt rotor aircraft. Personal experience shows that: (1) only a limited number of aircraft routes are explored; (2) operating costs are not explicitly considered; and (3) PMC plans may take up to 12 hours to create. This thesis develops and implements the PMC Route Optimizing Program (PROP), an optimization-based decision support system. PROP output prescriptions provide aircraft takeoff and landing times, routes, and transported PMC—everything required for planning PMC missions. We demonstrate PROP using 18 realistic test cases with up to four aircraft, five pickup and delivery locations, and up to 500 PMC requests. All test cases solve in less than one hour.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

ARG	Amphibious Ready Group
ATEM	Air Tasking and Efficiency Model
CSV	comma-separated values
DOW	distance-over-the-water
GAMS	General Algebraic Modeling System
HOSTAC	Helicopters Operating from Ships Other Than Aircraft Carriers
ICAO	International Civil Aviation Organization
$ICAO^+$	ICAO airport code and ship identifiers
LHD	amphibious assault ship
LPD	amphibious transport dock ship
LPH	landing platform helicopter
LSD	dock landing ship
MASHPAT	Marine Assault Support Helicopter Planning Assistance Tool
MIP	mixed-integer program
PMC	passengers and cargo
PROP	PMC Route Optimizing Program
PROP GUI	PMC Route Optimizing Program graphical user interface
SOCAL	Southern California
VBA	Visual Basic for Applications
VRP	Vehicle Routing Problem

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

An Amphibious Ready Group (ARG) consists of ships capable of conducting flight operations that routinely require the transport of passengers and cargo (PMC) to remain operationally viable. Route selection for rotary wing and tilt rotor aircraft (henceforth aircraft) includes aggregating PMC demand from paper forms and manually pairing demand to aircraft for transport. Personal experience shows that: (1) only a limited number of aircraft routes are explored; (2) operating costs are not explicitly considered; and (3) plans may take up to 12 hours to create.

This thesis develops and implements the PMC Route Optimizing Program (PROP), an optimization-based decision support system. PROP includes two-parts: (1) a graphical user interface that aids PMC data input and communicates to solution software and (2) a mixed-integer program that generates PMC planning solutions. PROP implicitly considers all feasible routes, minimizes operating costs, significantly reduces planning time, and ensures the unique PMC planning constraints are satisfied. PROP output prescriptions provide aircraft takeoff and landing times, routes, and transported PMC -- everything required for PMC mission planning.

We demonstrate PROP using 18 realistic test cases with up to four aircraft, five pickup and delivery locations, and up to 500 PMC requests. All test cases solve in less than two minutes when blocks of available time for aircraft and/or ships are contiguous and within a one-hour time limit for all others.

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to thank my family: Josie, Kayla, Connor, and McKay. Throughout my time at the Naval Postgraduate School, you constantly reminded me of what is truly important.

To Professor Robert Dell, I offer my sincere gratitude for your patience and thoughtful direction throughout the development of this thesis. Simply stated, without you, this project would never have been completed. It has been a pleasure working with and learning from you.

I would like to thank LCDR Connor “Sloppy” McLemore. Your encouragement and operational expertise brought this thesis to life and ensured its real-world relevance. It was fun working with you again; I hope to do so again in the future.

I would also like to acknowledge Professor Jerry Brown’s efforts as my second reader. Thank you for your time, guidance, and ridiculously quick “turn-arounds.”

Finally, I want to thank all of the optimizer professors at the Naval Postgraduate School. On several occasions, you fielded my “drive-by” questions, allowing me to push past hurdles along the way. Your willingness to drop everything to help me is a testament to your professionalism and dedication.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION TO PMC PLANNING

A. PURPOSE AND OVERVIEW

Currently, manually planning the daily transport of passengers and cargo (PMC) across an Amphibious Ready Group (ARG) is labor intensive and often results in the inefficient use of rotary wing and tilt rotor aircraft (henceforth aircraft). Pickup and delivery locations in an ARG consist of ships and nearby airfields. Route selection for aircraft entails aggregating PMC demand from paper forms and manually pairing PMC requests to aircraft for transport. Personal experience shows that: (1) only a limited number of aircraft routes are explored; (2) operating costs are not explicitly considered; and (3) each plan may take up to 12 hours to create. This thesis develops and implements the PMC Route Optimizing Program (PROP), an optimization-based decision support system. PROP promises to reduce planning time significantly with its user-friendly graphical user interface for optimizing airlift routing. Using a mixed-integer program (MIP), PROP output prescriptions provide aircraft takeoff and landing times, routes, and transported PMC.

A typical ARG consists of three to four ships (see Figure 1). PMC transport takes place between the ships and nearby airfields. Airfields are identified by an International Civil Aviation Organization (ICAO) airport code. In this thesis, we use $ICAO^{+}$ to refer to both airfield locations and ship locations. Common aircraft used to transport PMC across an ARG include the MH-60 Seahawk, CH-53 Sea Stallion and MV-22 Osprey. Figure 2 shows a picture of a MH-60S during a PMC mission. Figure 3 shows a CH-53 and Figure 4 a V-22.

Figure 1. The Bataan ARG. Each ARG ship routinely requires PMC support. Moving clockwise from top center: USS Fort McHenry (LSD 43), USS Bataan (LHD 5), USS Ponce (LPD 15), and USS Anzio (CG 68) (from U.S. Marine Corps 2009)

Figure 2. In the East China Sea, U.S. Marines board an MH-60S helicopter for transport off the USS Green Bay (LPD 20); a contingent of the BONHOMME RICHARD ARG (from U.S. Navy 2015a)

Figure 3. PMC mission complete. U.S. Marines disembark a CH-53 after landing on the USS Fort McHenry (LSD 43) (from U.S. Navy 2015b)

Figure 4. Tilt rotor operations. A V-22 Osprey lifts off of the USS Boxer (LHD 4) flight deck. The Osprey is set to replace the aging fleet of U.S. Marine Corps transport aircraft (from Military-Today.com n.d.)

The ARG produces a document daily called the airplan to dictate aircraft flights, including those used to transport PMC. The daily airplan is an essential communication link between aircrew, flight deck crew, and air controllers and is the central document that orchestrates flight operations. Without an airplan, coordinated flight operations become virtually impossible. Figures 5 and 6 show an airplan excerpt from the combined Exercise SSANG YONG by the ESSEX ARG and Republic of Korea in 2011 where over 30 aircraft conducted large-scale amphibious assault exercises. The ships involved in the exercise included the USS ESSEX (LHD 2), USS BONHOMME RICHARD (LHD 6), USS DENVER (LPD 9), USS TORTUGA (LSD 46), and ROKS DOKDO (LPH 6111).

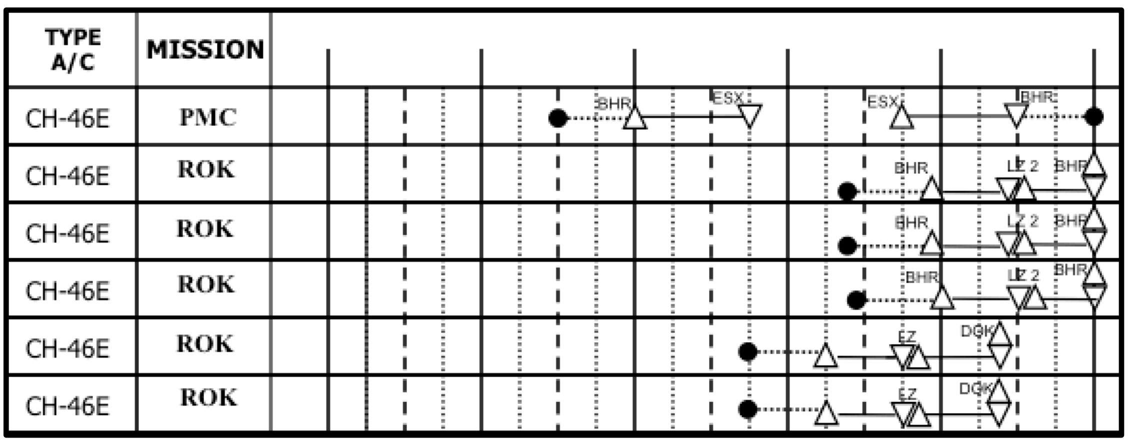

Figure 5. Draft airplan excerpt from Exercise SSANG YONG 2011. Helicopter line items detail aircraft-type, mission-type, and takeoff and landing times (times not shown) with the associated ICAO+.

Legend:
- Time to position aircraft on the flight deck
- Time to secure aircraft after flight operations
- ICAO+ Aircraft takeoff time with departure ICAO+
- ICAO+ Aircraft landing time with destination ICAO+

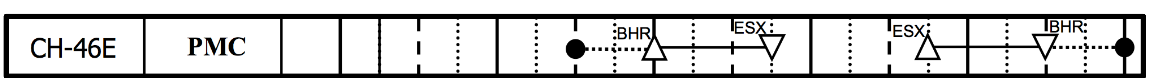

Figure 6. Airplan line from Figure 5. Here, the airplan tasks a CH-46E to conduct a PMC mission taking off from and returning to the USS BONHOMME RICHARD (BHR) after transporting PMC to the USS ESSEX (ESX).

Airplan development considers three types of aircraft missions: operational, training, and PMC. For each airplan, aircrew and ship-operation stakeholders allocate aircraft to each mission-type. Considerations for operational and training missions vary day-to-day and are not addressed in this thesis. In contrast, PMC planning considerations are virtually homogenous allowing for the development of a single system that can be used regardless of the ARGs operating environment.

The PMC portion of each airplan (henceforth PMC-airplan) seeks to move as much PMC as possible, with a limited number of aircraft. The PMC coordinator, an officer on the ARG staff, manually compiles and prioritizes all PMC requests, plans aircraft routes, and disseminates flight manifests for each aircraft. For typical PMC-airplans with only one or two aircraft and two or three ICAOs$^+$, manual PMC planning is usually adequate. As the number of aircraft, ICAOs$^+$, and/or PMC requests increase, the PMC-airplan becomes larger and increasingly difficult to plan manually. There are simply too many routing options available and aircraft constraints to consider all possibilities. From the author's personal experience, developing the PMC-airplan requires at least one hour while a more complex one often requires up to 12 hours.

The PMC coordinator currently uses pen-and-paper calculations in a tedious and time-consuming effort to produce the PMC-airplan with no guarantee that aircraft are being used efficiently. Furthermore, PMC-airplans do not build upon prior solutions. Each PMC-airplan is unique and therefore each PMC routing solution must be generated each day from scratch.

PMC planning requires consideration of constraints unique to ARG operations. We define the ARG PMC planning constraints as:

1. Section: A section is two aircraft flying the same route at the same time. Depending on the ICAO$^+$ to ICAO$^+$ distance-over-the-water (DOW), aircraft may require section support. DOW is the great-circle distance travelled over the water by an aircraft flying an arc between two ICAOs$^+$. Figure 7 provides an example of section requirements mandated for PMC transport.

Distance:	Ship-to-Ship	Ship-to-Shore	Shore-to-Ship
Less than 10nm	1,3,4,6	1,3,4,6	1,3,4,6
10nm to 25nm	1,3,4,7	1,3,4,7	1,3,4,7
25nm to 50nm	2,3,4,5,8	2,3,4,5,8	2,3,4,5,8
50nm to 75nm	N/A	2,3,4,5,8	2,3,4,5,8
More than 75nm	N/A	2,3,4,5,9	N/A

1 - May be flown single A/C
2 - Will be flown by multiple A/C
3 - Flown under constant radar flight following
4 - Voice Comm and TACAN lock with either departure or destination must be maintained throughout flight.
5 - Flight requires squadron commander's approval
6 - Weather shall be at least 500/1
7 - Weather shall be at least 800/2
8 - Weather shall be at least 1000/3
9 - Weather shall be at least 3000/5

Figure 7. Standard operating procedures for flight operations (from Damren 2010). This portion of the standard operating procedures for flight operations applies to rotary wing aircraft and dictates section requirements. As an example, for “Ship-to-Ship” flights with a “Distance” between “25nm to 50nm” the requirements are “2,3,4,5,8” where aircraft need: “2” section support, “3” air traffic control services, “4” working communication and navigation equipment, “5” commanding officer approval, “8” a cloud ceiling that is not less than 1,000 feet above ground level and visibility of at least 3 nm. “N/A” indicates the flight is not authorized for the given “Distance.” Note that “Distance” is equivalent to DOW.

2. Helo Time: A block of time when aircraft are available to conduct PMC missions. Generally, aircraft have one or two time blocks each day.

3. $ICAO^+$ Block: A block of time when an $ICAO^+$ is available to conduct flight operations. Time blocks define when an $ICAO^+$ can conduct flight operations (Figure 8).

<table>
<tr><td></td><td colspan="9">TIME</td></tr>
<tr><td></td><td>08:00</td><td>09:00</td><td>10:00</td><td>11:00</td><td>12:00</td><td>13:00</td><td>14:00</td><td>15:00</td><td>16:00</td></tr>
<tr><td>ICAO+ A</td><td></td><td colspan="8">TIME BLOCK 1</td></tr>
<tr><td>ICAO+ B</td><td colspan="4">TIME BLOCK 1</td><td></td><td></td><td colspan="3">TIME BLOCK 2</td></tr>
</table>

Figure 8. Generic ICAO+ example showing the times an ICAO+ may conduct flight operations. In this example, "ICAO+ A" can conduct flight operations from 09:00-16:00. "ICAO+ B" cannot conduct flight operations between 1200-1400 and therefore has two time blocks: 08:00-12:00 and 14:00-16:00.

4. Start/End: In PMC planning, it is necessary to control an aircraft's starting and ending ICAO+ each day. The start-ICAO+ and end-ICAO+ can be different.

5. HOSTAC: *Helicopters Operating from Ships other Than Aircraft Carriers* (North Atlantic Treaty Organizations, 2013). The HOSTAC publication documents if specific aircraft can (or cannot) conduct flight operations onboard specific ships.

B. BACKGROUND OF AIR ASSET ROUTING

Determining routes for aircraft transporting PMC is a vehicle routing problem (VRP). While much has been published on VRPs, there is no work that directly addresses the unique considerations for PMC-airplan development. Below, we provide references specific to similar aircraft routing and a recent survey on VRPs with synchronization.

Qian, Gribkovskaia and Halskau (2011) develop a VRP with pickup and deliveries. With the view that helicopter transportation poses a major hazard to personnel, their VRP with pickup and deliveries routes oil platform service helicopters with the objective of minimizing the expected number of fatalities. Helicopter operations include routine shift turnover every 14 days, irregularly timed site visits, and unplanned equipment repair trips. In comparing the expected number of casualties versus flying time for one to seven helicopters flying to ten oil platforms, they minimize the expected number of fatalities with the CPLEX 9.0 solver. The CPLEX solution allows decision makers to balance enhanced risk-mitigation versus reduced travel time.

Timlin and Pulleyblank (1992) develop a precedence-constrained traveling salesman heuristic for helicopter planning. Tasked with planning 12 helicopter routes daily to service 45 oil platforms, Timlin and Pulleyblank seek to “find [the] shortest schedule that avoids overloading the helicopter” (page 101). Their heuristic prioritizes oil platform service requirements and constrains the path to include a single start-end node while ensuring throughput does not exceed the helicopter’s single-leg capacity. A leg is simply a single flight between two locations.

Moreno, Aragao, and Uchoa (2006) develop a column generation-based heuristic for a helicopter routing problem. Their task includes planning 70 flights per day for 35 helicopters to move approximately 42,000 passengers per month. Model constraints include managing helicopter passenger capacities and destination on- and off-load times where the objective is to minimize operating costs for different helicopter types. Route planning is restricted to a defined helicopter departure time and routes helicopters from and to a single home base location.

Brown, Carlyle, Dell, and Brau (2013) develop an integer linear program as the backbone of their Air Tasking Efficiency Model (ATEM). ATEM serves to reduce ground transport exposure to improvised explosive devices by maximizing airlift movement of personnel and cargo. ATEM accounts for multi-commodity delivery and throughput of personnel and cargo with time constraints. All feasible aircraft routes, bounded by operational constraints, are enumerated with the optimal route chosen for each aircraft. Optimality is defined as maximizing the transport of prioritized cargo.

Building on ATEM, Wray (2009) develops the Marine Assault Support Helicopter Assistance Tool (MASHPAT) using a greedy heuristic. MASHPAT routes approximately 15 helicopters daily to 25 forward operating bases to meet anywhere from 50 to 125 cargo requests. MASHPAT accommodates cargo-types with varying weights, volumes, and priorities; helicopter limitations such as maximum fuel and cargo capacities; and feasible route selection based on

current threats and helicopter endurance. Field-testing shows that the required planning cycle is reduced to less than an hour, when compared to several hours before implementation of the program.

Drexl (2012) surveys vehicle routing problems with multiple synchronization constraints compiling a list of over 120 references. Arguing that vehicle routes may not be independent of each other, Drexl defines five sub-classes of VRPs with multiple synchronization constraints: task, operation, movement, load, and resource synchronization. Task synchronization requires a specified action to be completed by at least one of the available vehicles. Operation synchronization provides vehicle time-delays at a node to allow for a task to be completed; the vehicle cannot continue on its route until the assigned job is done. Movement considers pairing vehicle-travel between nodes along an arc where arrival and departure times are equated for each vehicle. Movement synchronization is the same sub-class of problem described in this thesis as a section requirement. Load synchronization ensures the load received at a node is equal to that which is offloaded from the vehicle. Finally, as vehicles move through the network, resource synchronization limits vehicle consumables.

From the previous work, there are many similar model attributes that extend to PMC-airplan development; particularly modeling multi-commodity throughput with capacitated vehicles under a many vehicles-to-many locations VRP construct. Also, several of the synchronization considerations from Drexl's paper are pertinent. However, we find that all the ARG PMC planning constraints are not explicitly addressed in past work, so we present a unique formulation.

C. SCOPE AND LIMITATIONS

This thesis develops a mixed-integer program (MIP) to effectively route PMC-tasked aircraft across an ARG. The model constraints are specific to rotary wing and tilt rotor flight operations and only consider PMC missions. Operational and training requirements are not addressed. The formulated constraints are

specifically tailored to ARG PMC flight operations. As such, the MIP is only for PMC planning and does not extend beyond ARG operations.

PMC Route Optimizing Program (PROP) calculates $ICAO^+$ to $ICAO^+$ distances, not $ICAO^+$ to shoreline distances (DOW) to determine section requirements. Depending on the shoreline geography, PROP may require a section for a particular leg when in reality a single aircraft could legally fly the leg. In such situations, visual inspection of the operating area is required to correctly determine section requirements.

In considering an aircraft's PMC capacity, PROP assumes separate capacities for passengers and cargo that cannot be adjusted en route. Aircraft seating capacity limits the number of passengers allowed to travel per leg. Cargo movements, on the other hand, are not as easily defined. Cargo can range from small, hand-held parts to large, heavy aircraft engines and anything in between. We define any such cargo as a cargo unit with aircraft capacity expressed in terms of cargo units. Given the unpredictable range of cargo possibilities, PROP treats each cargo request as a single cargo unit absent size and weight considerations. It is incumbent on the PMC coordinator to ensure that the total cargo unit request per leg does not exceed the aircraft's weight and volume limitations.

D. THESIS ORGANIZATION

Chapter II details the MIP used in PROP. Sets, parameters, variables, and constraints are defined and explained. Chapter III describes the beginning-to-end steps in PROP for a single PMC scenario and analyzes 18 test cases. In Chapter IV, PROP conclusions and future work are discussed.

II. THE PROP MIXED-INTEGER PROGRAM

A. INTRODUCTION

This chapter describes the PROP MIP with details on assumptions, data, variables, and constraints.

B. ASSUMPTIONS

PMC planning requires assumptions about PMC operations, and ARG operations in general. PROP assumptions include:

1. Deck delays. Time spent at each ICAO$^+$ includes the terminal-area approach, the loading and unloading of PMC, aircraft refueling, and aircrew swaps.
2. The relative positions of ships are static. Relative ICAO$^+$-to-ICAO$^+$ distances are constant for each PMC-airplan.
3. Fixed number of legs. Aircraft are afforded a fixed number of PMC-airplan flight legs per day.
4. Aircraft section takeoff times. Takeoff times for section aircraft must be within a PMC coordinator-defined number of minutes of each other (e.g., five minutes).

What follows in the next four sections is a detailed description of the sets, parameters, variables, and MIP formulation.

C. SETS

$i \in I$	departure ICAO$^+$
$j \in J$	destination ICAO$^+$
$k \in K$	PMC type; passenger or cargo
$l \in L$	aircraft stop, an ordinal index (e.g., $L = \{l_0, l_1, ..l_{10}\}$)
$h \in H$	aircraft type

$h \in RW$	rotary wing aircraft
$h \in TR$	tilt rotor aircraft
$(i,j) \in ARCS$	all ICAO^{+} pairings
$(i,j,h) \in HARC$	allowable i to j pairings for aircraft h
$(i,j,h) \in SARC$	i to j pairings that require section support for aircraft h

D. PARAMETERS

$cap_{h,k}$	maximum carrying capacity of aircraft h for PMC-type k
$cost_h$	aircraft h operating cost in dollars per minute
$trans_{i,j,h}$	aircraft h transit time in minutes from i to j

$$= \frac{dist_{i,j}}{speed_h} \text{ where,}$$

$dist_{i,j}$ is the distance in nautical miles from i to j and,

$speed_h$ is aircraft h speed in nautical miles per minute

$start_{h,i}$	1 if aircraft h commences flight operations at i
$end_{h,j}$	1 if aircraft h concludes flight operations at j
$dem_{i,j,k}$	demand for PMC-type k to be transported from i to j
$delay_{l,h}$	minimum deck delay in minutes for aircraft h at stop l
$maxsect$	maximum takeoff time difference between two aircraft flying a section requirement

$maxflt$	maximum total time in minutes to conduct flight operations
$neticao2_j$	earliest time j can conduct flight operations in block 2
$nlticao2_j$	latest time j can conduct flight operations in block 2
$net_{j,h}$	no-earlier-than arrival time at j for aircraft h; $= \max(neth_h neticao1_j)$ where, $neth_h$ is the no-earlier-than time that aircraft h can conduct flight operations and, $neticao1_j$ is the no-earlier-than time that j can conduct flight operations in block 1
$nlt_{j,h}$	no-later-than arrival time at j for aircraft h; $= \min(nlth_h nlticao1_j)$ where, $nlth_h$ is the no-later-than time that aircraft h can conduct flight operations and, $nlticao1_j$ is the no-later-than time that j can conduct flight operations in block 1
$pen_{i,j,k}$	penalty per unit of PMC-type k not moved from i to j
$tpen_{l,h}$	penalty for aircraft h at the l^{th} takeoff (cost that increases as l increases)
$costm_l$	penalty incurred for flying leg l (cost that increases as l increases)

E. VARIABLES

$X_{i,j,l,h}$	1 if aircraft h flies i to j as the l^{th} stop, 0 otherwise
$T_{l,h}$	landing time for aircraft h at the l^{th} stop

$E_{i,j,k}$	units of PMC-type k not moved from i to j
$M_{i,l,j,l',k,h}$	integer units of PMC-type k moved on aircraft h from i as stop l to j as stop l' where $l' > l$
$TH_{h,h'i,j,l,l'}$	1 if $X_{i,j,l,h}$ = 1 and aircraft h requires section support from i to j, 0 otherwise; aircraft h' is the *supporting* aircraft and does not necessarily require section support
$BL_{j,l,h}$	1 if aircraft h lands at j and the l th stop is in time block 2; 0 otherwise
$BT_{i,l,h}$	1 if aircraft h departs i and the l th stop is in time block 2; 0 otherwise

F. FORMULATION

$$\min \sum_{(i,j,h)|(i,j,h)\in HARC} \sum_{l} cost_h trans_{i,j,h} X_{i,j,l,h} + \sum_{(i,j)|(i,j)\in ARCS} \sum_{k} pen_{i,j,k} E_{i,j,k} \quad (0)$$
$$+ \sum_{(i,j,h)|(i,j,h)\in HARC} \sum_{(l,l')|l<l'} \sum_{k} costm_l M_{i,l,j,l',k,h} + \sum_{l} \sum_{h} tpen_{l,h} T_{l,h}$$

$$T_{l+1,h} \geq T_{l,h} + \sum_{(i,j)|(i,j,h)\in HARC} (trans_{i,j,h} + delay_{l,h}) X_{i,j,l+1,h} \qquad \forall l,h \quad (1)$$

$$BL_{j,l,h} \leq \sum_{i|(i,j,h)\in HARC} X_{i,j,l,h} \qquad \forall j,l,h \quad (2)$$

$$BT_{i,l,h} \leq \sum_{j|(i,j,h)\in HARC} X_{i,j,l,h} \qquad \forall i,l,h \quad (3)$$

$$T_{l,h} \geq \sum_{(i,j)|(i,j,h)\in HARC} net_{j,h} X_{i,j,l,h} + \sum_{j} (neticao2_{j} - net_{j,h}) BL_{j,l,h} \qquad \forall l \mid l > 1, h \tag{4}$$

$$T_{l,h} \leq \sum_{(i,j)|(i,j,h)\in HARC} nlt_{j,h} X_{i,j,l,h} + \sum_{j} (nlticao2_{j} - nlt_{j,h}) BL_{j,l,h} \qquad \forall l \mid l > 1, h \tag{5}$$

$$T_{l,h} \geq \sum_{(i,j)|(i,j,h)\in HARC} (net_{i,h} + trans_{i,j,h}) X_{i,j,l,h} + \sum_{i} (neticao2_{i} - net_{i,h}) BT_{i,l,h} \qquad \forall l \mid l > 1, h \tag{6}$$

$$T_{l,h} \leq \sum_{(i,j)|(i,j,h)\in HARC} (nlt_{i,h} + trans_{i,j,h}) X_{i,j,l,h} + \sum_{i} (nlticao2_{i} - nlt_{i,h}) BT_{i,l,h} \qquad \forall l \mid l > 1, h \tag{7}$$

$$X_{i,j,l,h} = \sum_{l',h'} TH_{h,h',i,j,l,l'} \qquad \forall (i,j,h) \in SARC, l \tag{8}$$

$$TH_{h,h',i,j,l,l'} \leq X_{i,j,l',h'} \qquad \forall (i,j,h) \in SARC, l, l', h \tag{9}$$

$$T_{l,h} - T_{l',h'} \leq maxsect(TH_{h,h',i,j,l,l'}) + maxflt(1 - TH_{h,h',i,j,l,l'}) \qquad \forall (i,j,h) \in SARC, l, l', h' \tag{10}$$

$$T_{l'-1,h'} - T_{l-1,h} \leq maxsect(TH_{h,h',i,j,l,l'}) + maxflt(1 - TH_{h,h',i,j,l,l'}) \qquad \forall (i,j,h) \in SARC, l, l', h' \tag{11}$$

$$\sum_{j|(i,j,h)\in HARC} X_{i,j,l_1,h} = 1 \qquad \forall h,i \mid start_{h,i} = 1 \qquad (12)$$

$$\sum_{i|(i,j,h)\in HARC} X_{i,j,l_{10},h} = 1 \qquad \forall h,j \mid end_{h,j} = 1 \qquad (13)$$

$$X_{i,j,l_1,h} = \sum_{i'|(i',j,h)\in HARC} X_{j,i',l_2,h} \qquad \forall (i,j,h) \in HARC \mid start_{h,i} = 1 \qquad (14)$$

$$\sum_{i|(i,j,h)\in HARC} X_{i,j,l,h} = \sum_{i|(i,j,h)\in HARC} X_{j,i,l+1,h} \qquad \forall j,l \mid l > 1,h \qquad (15)$$

$$\sum_{(l,l')|l<l',h} M_{i,l,j,l',k,h} \geq dem_{i,j,k} - E_{i,j,k} \qquad \forall (i,j) \in ARCS,k \qquad (16)$$

$$\sum_{i,l|l<l'} M_{i,l,j,l',k,h} \leq cap_{h,k} \sum_{i|(i,j,h)\in HARC} X_{i,j,l',h} \qquad \forall j,l',h,k \qquad (17)$$

$$\sum_{j,l'|l'>l} M_{i,l-1,j,l',k,h} \leq cap_{h,k} \sum_{j|(i,j,h)\in HARC} X_{i,j,l,h} \qquad \forall i,l,h,k \qquad (18)$$

$$\sum_{i,j} \sum_{l'|l'<l} \sum_{l''|l''>l} M_{i,l',j,l'',k,h} \leq cap_{h,k} \qquad \forall l,h,k \qquad (19)$$

$$X_{i,j,l,h} \in \{0,1\} \qquad \forall i,j,l,h$$

$$T_{l,h} \geq 0 \qquad \forall l,h$$

$$E_{i,j,k} \in \{0,1,2,3...\} \qquad \forall i,j,k$$

$$M_{i,l,j,l',k,h} \in \{0,1,2,3,...\} \qquad \forall i,l,j,l',k,h$$

$$TH_{h,h',i,j,l,l'} \in \{0,1\} \qquad \forall h,h',i,j,l,l'$$

$$BL_{j,l,h} \in \{0,1\} \qquad \forall j,l,h$$

$$BT_{i,l,h} \in \{0,1\} \qquad \forall i,l,h$$

G. DISCUSSION

The objective function, equation (0), expresses aircraft operating costs in dollars, a penalty for unmet demand ($pen_{i,j,k}$), and additional penalties to encourage early delivery. The value of $pen_{i,j,k}$ requires careful consideration. If set too low, nothing moves. If set too high, a single PMC request may be moved at an exceedingly high cost.

The objective function includes two other penalties: $costm_l$ and $tpen_{l,h}$ to encourage early use of legs and avoid any waiting at stops that are not required for operations. In early PROP development, prior to including $costm_l$, aircraft remained at the same ICAO$^+$ for several stops (at zero cost) without delivering any PMC. Adding an incrementally larger cost to each successive leg adds a sense of urgency to accomplish the PMC mission and legs no longer go needlessly unutilized.

Each constraint (1) defines the earliest feasible landing time for an aircraft at one of its stops. Each constraint (2) and (3) governs the respective landing and takeoff event with the decision to fly a leg including these events.

For a given aircraft and stop, a constraint (4), (5), (6), and (7) defines the earliest to latest admissible landing time at that stop. Each constraint (4) and (5) defines the admissible aircraft takeoff time at that stop and each constraint (6) and (7) defines the admissible aircraft landing time at that stop.

For an aircraft at one of its stops, each constraint (8) defines the event of an aircraft flying an $ICAO^+$-to-$ICAO^+$ pairing that requires section support. For two given aircraft at non-contiguous stops flying an $ICAO^+$-to-$ICAO^+$ pairing that requires section support for one of the aircraft, each constraint (9) defines the event of one aircraft satisfying the other aircraft's section requirement.

For two given aircraft, each with non-contiguous stops relative to the other, a constraint (10) and (11) restricts the maximum takeoff time difference between the two aircraft. In general, the allowable time difference for two aircraft that satisfy an $ICAO^+$-to-$ICAO^+$ pairing section requirement is $maxsect$. The allowable time difference for any aircraft not satisfying an $ICAO^+$-to-$ICAO^+$ pairing section requirement is $maxflt$.

For a given aircraft and its departure $ICAO^+$, each constraint (12) restricts the first takeoff event for that aircraft to occur from the PMC coordinator-defined starting $ICAO^+$. For a given aircraft and its destination $ICAO^+$, each constraint (13) restricts the last landing event for that aircraft to occur at the PMC coordinator-defined ending $ICAO^+$.

For a given aircraft at one of its stops, a constraint (14) and (15) ensures the aircraft's next take off is from that stop. Each constraint (14) governs the aircraft's first takeoff event, while each constraint (15) governs the remaining takeoff events.

For a given cargo-type and $ICAO^+$-to-$ICAO^+$ pairing, each constraint (16) measures unmoved PMC demand and forces the movement of PMC as this appears in the objective function with a penalty. For a given aircraft flying to its next stop, each constraint (17) limits the total amount of cargo-type moved to this stop (destination $ICAO^+$). For a given aircraft departing its previous stop, each constraint (18) limits the total amount of cargo-type moved from this stop (departure $ICAO^+$). For a given cargo unit and aircraft at one of its stops, each constraint (19) limits the total aircraft cargo unit-type moved by considering the

total amount of cargo-type carried though this intermediate stop (but not delivered), en route to the cargo unit’s destination stop.

THIS PAGE INTENTIONALLY LEFT BLANK

III. PROP IMPLEMENTATION AND RESULTS

A. INTRODUCTION

We use PROP to solve 18 PMC test scenarios modeled after previously developed real-world PMC-airplans. We use a 2.4 GHz Intel Core i7™ MacBook PRO running Windows 7 operating system through VMware. PROP generates all MIP instances using GAMS (2013) and solves them using the CPLEX solver. Microsoft Office 2010, Version 14.0.7135.5000, Excel Visual Basic for Applications code (VBA) generates the PMC data. Prior to running the trials, we tune $pen_{i,j,k}$ to ensure PROP behaves in a manner consistent with real-world PMC planning.

B. TUNING THE PENALTY FOR UNMET DEMAND

To tune the $pen_{i,j,k}$ value, we compare the operating costs to transport five passengers for varying round-trip aircraft times. We choose five based on personal experience; it is a reasonable measure of what resources we are willing to expend versus what PMC requests we are willing to deny or delay. By analyzing the operating costs for a range of flight times, we can equate the cost to move the five passengers to $pen_{i,j,k}$ (Table 1).

Total flight time (minutes)	Aircraft cost (dollars/minute)	Total cost (dollars)	Cost per person for five passengers (dollars)
50	170	8,000	1,600
60	170	10,200	2,040
70	170	11,900	2,380
80	170	13,600	2,720
90	170	15,300	3,060
100	170	17,000	3,400
110	170	18,700	3,740
120	170	20,400	4,080
130	170	22,100	4,420

Table 1. Operating costs for varying round-trip times. Total flight time includes the round-trip and deck delay time. Aircraft cost is for a CH-53. Total cost is the Total flight time multiplied by the Aircraft cost. Cost per person for five passengers is the Total cost divided by five.

For typical ARG ICAO$^+$ ship positioning, normal round-trip flight times are between 50 to 130 minutes. Table 1 shows us that for such flight times, reasonable $pen_{i,j,k}$ values range from \$1,600 to \$4,420. We expand the range to \$1,000 to \$5,000 and conduct eight tuning trials to determine an appropriate $pen_{i,j,k}$ value. From the tuning trials, we choose a $pen_{i,j,k}$default value of \$4,000. This $pen_{i,j,k}$ balances operating costs with the cost of conducting PMC missions.

C. SOUTHERN CALIFORNIA (SOCAL) PROP EXAMPLE

This section illustrates PROP steps for a single PMC planning instance we call the SOCAL PROP example. We start with the PROP graphical user interface (PROP GUI) and explain each step the PMC coordinator takes to capture the PMC demand, define the PMC scenario, and implement the required constraints. We then analyze the results.

In our example, there are four ICAOs$^+$: USS ESSEX (ESX), USS BONHOMME RICHARD (BHR), USS GREEN BAY (GBY), and Naval Air Station

North Island (NZY). Figure 9 shows the geographical locations of the ICAOs+ located in Southern California.

Table 2 shows the data for the three aircraft available for PMC missions: 1CH53, 2CH53, and 3V22. The number preceding the aircraft-type uniquely identifies each aircraft; each aircraft starts and ends at ESX. Aircraft availability and ICAO+ time blocks are in Table 3 and the ICAO+ to ICAO+ demand is in Table 4. There are a total of 308 passengers and 2 cargo units requesting PMC transport. Table 5 identifies viable HOSTAC pairings and Table 6 enumerates the section requirements for each aircraft type based on aircraft type and the ICAO+ to ICAO+ distances.

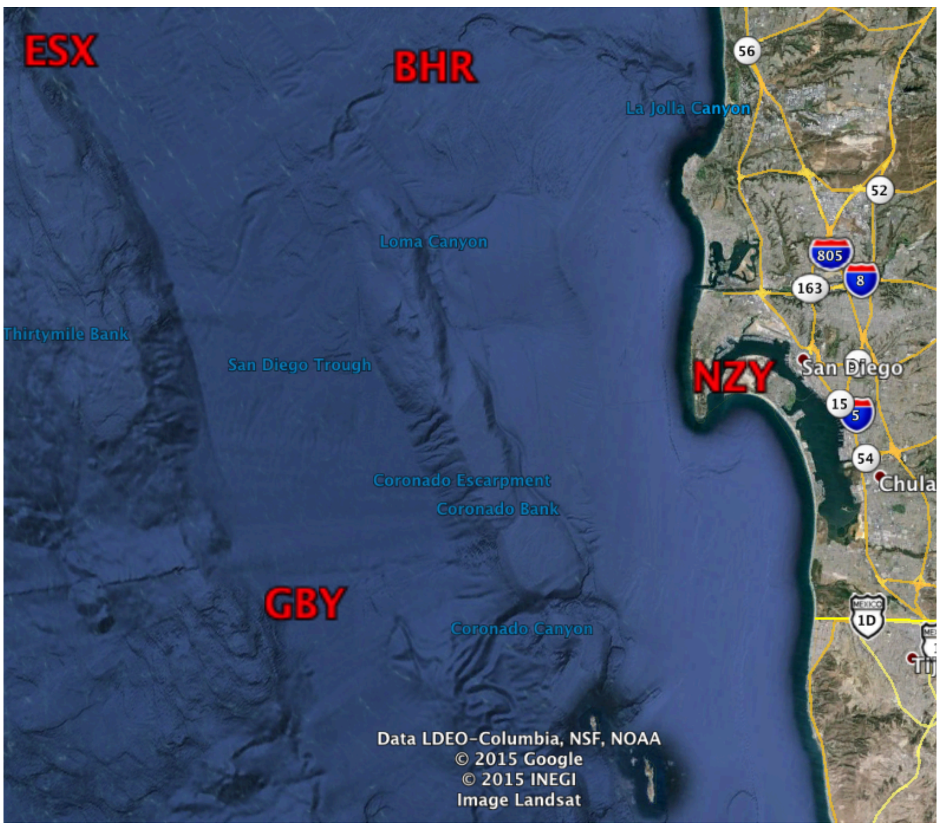

Figure 9. ICAO+ geographical locations for the SOCAL PROP example. ICAOs+ are shown in red text. The ESX, BHR, and GBY are ships while NZY is an airport located in Coronado, CA. (Image 2015 Google Inc.)

Aircraft	Speed (knots)	Operating cost (dollars/hour)	Max capacity (passengers)	Max capacity (cargo)	Deck delay (minutes)
1CH53	100	9,600	24	2	30
2CH53	100	9,600	24	2	30
3V22	200	10,200	24	2	45

Table 2. Example aircraft data for the SOCAL PROP example. 1CH53 flies at 100 knots at a cost of $9,600 per hour, can carry up to 24 passengers and 2 cargo units per leg, and has a deck delay of 30 minutes. The PMC coordinator populates PROP with this data prior to PMC planning.

The following parameter values are hard-coded into PROP:

- $maxsect$ = 5 minutes
- $maxflt$ = 960 minutes
- $pen_{i,j,k}$ = $4,000

<table>
<tr><th rowspan="2"></th><th colspan="9">TIME AVAILABILTY FOR AIRCRAFT AND ICAOs$^+$</th></tr>
<tr><th>0800</th><th>0900</th><th>1000</th><th>1100</th><th>1200</th><th>1300</th><th>1400</th><th>1500</th><th>1600</th></tr>
<tr><td>ESX</td><td colspan="9">BLOCK 1</td></tr>
<tr><td>BHR</td><td colspan="9">BLOCK 1</td></tr>
<tr><td>GBY</td><td colspan="9">BLOCK 1</td></tr>
<tr><td>NZY</td><td colspan="3">BLOCK 1</td><td colspan="2"></td><td colspan="4">BLOCK 2</td></tr>
<tr><td>1CH53</td><td colspan="9">AIRCRAFT AVAILABILITY</td></tr>
<tr><td>2CH53</td><td colspan="9">AIRCRAFT AVAILABILITY</td></tr>
<tr><td>3V22</td><td colspan="9">AIRCRAFT AVAILABILITY</td></tr>
</table>

Table 3. Aircraft availability and ICAO$^+$ time blocks for the SOCAL PROP example. Shaded times indicate aircraft availability to fly PMC missions and when an ICAO$^+$ can conduct flight operations. For example, flight operations at NZY are allowed from 08:00-11:00 (block 1) and 13:00-16:00 (block 2); 3V22 is available for PMC missions from 08:00-16:00.

FROM \ TO	ESX	BHR	GBY	NZY
ESX	0,0	10,0	30,0	80,0
BHR	16,0	0,0	16,0	0,0
GBY	0,0	26,0	0,0	20,0
NZY	100,1	0,0	10,1	0,0

Table 4. ICAO$^+$ to ICAO$^+$ PMC demand for the SOCAL PROP example. Passenger and cargo demand pairs are shown for each ICAO$^+$ pairing (number of passengers, number of cargo units). For example, from NZY to GBY there are PMC requests (10,1) to move 10 passengers and 1 cargo unit.

	ESX	BHR	GBY	NZY
1CH53	1	1	1	1
2CH53	1	1	1	1
3V22	1	1	0	1

Table 5. HOSTAC information for the SOCAL PROP example. “1” indicates the aircraft can fly to the ICAO$^+$ while “0” indicates that aircraft cannot. In this example, the 3V22 cannot fly to GBY, while all other parings are allowed. The disallowed 3V22 to GBY pairing is for demonstration purposes; V-22 aircraft are not normally restricted from landing onboard the GBY.

FROM \ TO	ESX	BHR	GBY	NZY
ESX	--	--	CH-53	CH-53
BHR	--	--	--	--
GBY	CH-53	--	--	--
NZY	CH-53	--	--	--

Table 6. Section Requirements for the SOCAL PROP example. “FROM” - “TO” combinations that require section support. For example, any CH-53 requires section support to fly from ESX to NZY. “--" indicates there is no section requirement for any aircraft. In this example, 3V22 does not require section support for any ICAO$^+$ to ICAO$^+$ pairings.

With the SOCAL PROP example defined, the PMC coordinator first populates the PMC request sheet as seen in Figure 10.

UPDATE MANIFEST | UPDATE FLY DAY

PRI	RANK	FIRST	LAST	SSN	Blood Type	From Node	To Node	STATUS	NET Date	NLT Date	UNIT	Mode of Travel	POC	CARGO TYPE
1	LCDR	Josie	LAST	1234	A	ESX	GBY	Pending	27-May-15	15-Jun-15	VAQ-137	AIR	Chuck Norris	pax
1	CPO	Kayla	LAST	1234	B	ESX	GBY	Pending	27-May-15	15-Jun-15	CVN76	AIR	Chuck Norris	pax
1	SGT	Connor	LAST	1234	O+	ESX	GBY	Pending	27-May-15	15-Jun-15	CVN80	AIR	Chuck Norris	pax
1	CDR	McKay	LAST	1234	A	ESX	GBY	Pending	27-May-15	15-Jun-15	CVN84	AIR	Chuck Norris	pax
1	LT	Dave	LAST	1234	B	ESX	BHR	Pending	27-May-15	15-Jun-15	CVN88	AIR	Chuck Norris	pax
1	LCDR	Mary	LAST	1234	O+	ESX	NZY	Pending	27-May-15	15-Jun-15	CVN92	AIR	Chuck Norris	pax
1	CPO	Kyle	LAST	1234	A	ESX	NZY	Pending	27-May-15	15-Jun-15	CVN96	AIR	Chuck Norris	pax
1	CDR	Heidi	LAST	1234	O+	ESX	NZY	Pending	27-May-15	15-Jun-15	CVN100	AIR	Chuck Norris	pax
1	LT	Hadleigh	LAST	1234	A	ESX	NZY	Pending	27-May-15	15-Jun-15	CVN104	AIR	Chuck Norris	pax
1	LCDR	Sierrah	LAST	1234	B	ESX	NZY	Pending	27-May-15	15-Jun-15	CVN108	AIR	Chuck Norris	pax
1	CPO	Johanna	LAST	1234	O+	ESX	NZY	Pending	27-May-15	15-Jun-15	CVN112	AIR	Chuck Norris	pax
1	SGT	Chris	LAST	1234	A	ESX	NZY	Pending	27-May-15	15-Jun-15	CVN116	AIR	Chuck Norris	pax
1	CDR	Isaac	LAST	1234	B	ESX	NZY	Pending	27-May-15	15-Jun-15	CVN120	AIR	Chuck Norris	pax
1	LCDR	Siena	LAST	1234	A	ESX	NZY	Pending	27-May-15	15-Jun-15	CVN124	AIR	Chuck Norris	pax
1	CPO	Roy	LAST	1234	B	ESX	NZY	Pending	27-May-15	15-Jun-15	CVN128	AIR	Chuck Norris	pax
1	SGT	Billie Jo	LAST	1234	O+	GBY	BHR	Pending	27-May-15	15-Jun-15	CVN132	AIR	Chuck Norris	pax
1	CDR	David	LAST	1234	A	GBY	BHR	Pending	27-May-15	15-Jun-15	CVN136	AIR	Chuck Norris	pax
1	LT	Michelle	LAST	1234	B	GBY	NZY	Pending	27-May-15	15-Jun-15	CVN140	AIR	Chuck Norris	pax
1	LCDR	Christa	LAST	1234	O+	GBY	NZY	Pending	27-May-15	15-Jun-15	CVN144	AIR	Chuck Norris	pax
1	CPO	Wade	LAST	1234	A	BHR	ESX	Pending	27-May-15	15-Jun-15	CVN148	AIR	Chuck Norris	pax
1	CDR	McKay	LAST	1234	O+	BHR	ESX	Pending	27-May-15	15-Jun-15	CVN152	AIR	Chuck Norris	pax
1	LT	Amy	LAST	1234	A	NZY	ESX	Pending	27-May-15	15-Jun-15	CVN156	AIR	Chuck Norris	pax
1	LCDR	Mackenzie	LAST	1234	B	NZY	ESX	Pending	27-May-15	15-Jun-15	CVN160	AIR	Chuck Norris	pax
1	CPO	Ryan	LAST	1234	O+	NZY	ESX	Pending	27-May-15	15-Jun-15	CVN164	AIR	Chuck Norris	pax
1	SGT	Anderson	LAST	1234	A	NZY	ESX	Pending	27-May-15	15-Jun-15	CVN168	AIR	Chuck Norris	pax
2	CDR	Adam	LAST	1234	O+	ESX	GBY	Pending	27-May-15	15-Jun-15	CVN74	AIR	Chuck Norris	pax
2	LT	Sarah	LAST	1234	B	ESX	GBY	Pending	27-May-15	15-Jun-15	CVN73	AIR	Chuck Norris	pax

Figure 10. The PROP opening manifest form with all PMC requests. The PMC coordinator enters all line-item PMC requests with the appropriate information. A description of each part of the manifest sheet follows.

PRI: Each PMC request has an associated PMC coordinator-defined priority. The lower the assigned number, the higher the priority. This priority is not part of the objective function. A PMC coordinator could use this priority to manually match each PMC request to the PROP prescription when not all PMC requests are met.

From Node: Starting ICAO+ for each PMC request.

To Node: Ending ICAO+ for each PMC request.

STATUS: There are two options: PENDING and COMPLETE. PENDING makes the request eligible for PMC transport and COMPLETE is used for archival purposes.

NET Date: Requested “no-earlier-than” date for PMC movement.

NLT Date: Requested “no-later-than” date for PMC movement.

Mode of Travel: AIR or SURFACE. This thesis only considers AIR PMC requests; however, surface PMC requests can also be tracked on this sheet.

CARGO TYPE: The PMC Coordinator categorizes the PMC-type as either passengers (pax in Figure 10) or cargo.

Administrative data: Data that is needed for a PMC traveller, but is not relevant to PROP: RANK, FIRST (name), LAST (name), SSN (last four social security digits), Blood Type, Unit, and POC (point of contact).

The following macro instructions (macros) are available in the PROP GUI:

UPDATE MANIFEST: macro that sorts PMC requests as follows:

- Higher-priority PMC requests take precedence over lower-priority requests.
- PMC requests of the same priority are sorted by the time between the “NET Date” and the PMC plan date. A PMC request that has waited longer for transport takes priority over requests with shorter wait times.

This prioritization scheme is local to each $ICAO^+$. Seats are filled according to the priority by leg of the PMC requests at that $ICAO^+$. This macro also archives all PMC requests labeled as STATUS: COMPLETE.

UPDATE FLYDAY: macro used to update the daily PMC scenario. There are three separate user-forms that gather $ICAO^+$ information (Figure 11), aircraft information (Figure 12), and HOSTAC information (Figure 13).

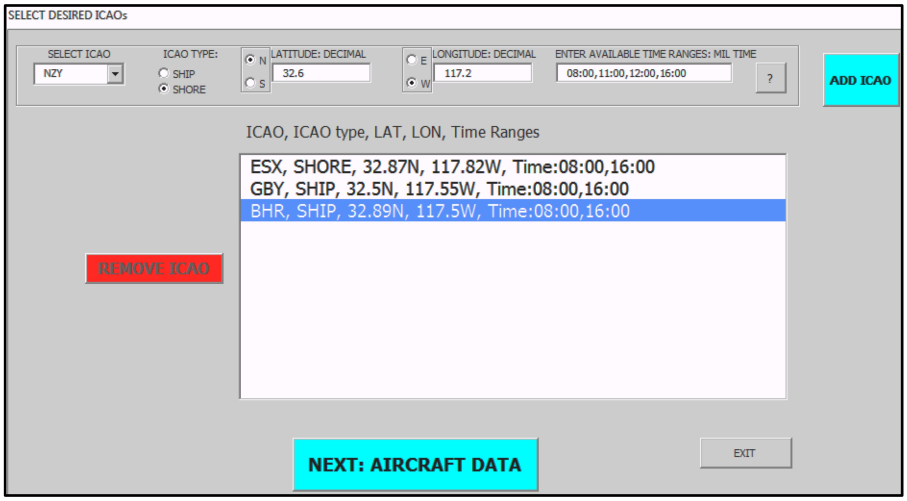

Figure 11. PROP ICAO$^+$ user-form. The PMC coordinator selects all ICAOs$^+$ to be considered for PMC planning, tags each as a ship or shore ICAO$^+$-type, geo-locates the ICAO$^+$ by latitude and longitude in decimal degrees, and enters the ICAO$^+$ time block(s). As an example, at the top, we see an entry about to be added for NZY as a SHORE ICAO$^+$ at 32.6° N and 117.2° W with time block 1: 08:00 to 11:00 and time block 2: 12:00 to 16:00.

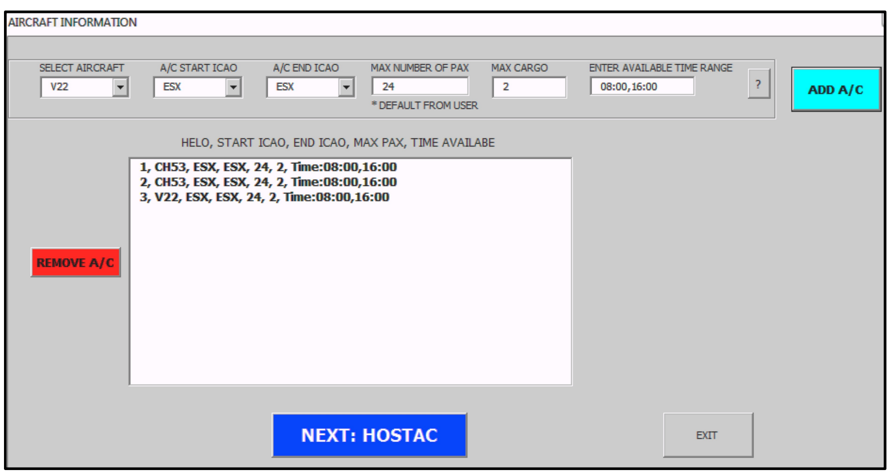

Figure 12. PROP aircraft user-form. The PMC coordinator selects the available PMC aircraft, delineates the start and end ICAOs$^+$, verifies the default PMC-type capacities are accurate, and enters the aircraft's availability time. For example, both CH-53s already entered start and end at ESX, can carry up to 24 passengers and 2 cargo units, and are available from 08:00 to 16:00.

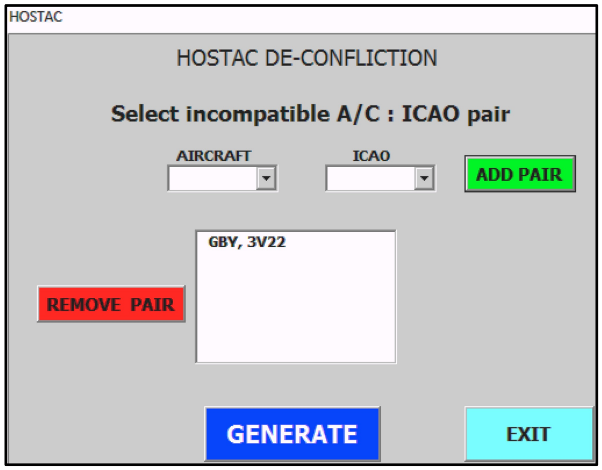

Figure 13. PROP HOSTAC user-form. The PMC coordinator identifies unavailable aircraft-ICAO+ pairings. All aircraft-ICAO+ parings are allowed unless otherwise indicated in this HOSTAC form. In this example, 3V22 cannot fly to the GBY.

The "GENERATE" macro on the PROP HOSTAC form creates 19 comma-separated value (CSV) files that contain all required data for GAMS (2013). CSV file generation takes between 10 to 20 seconds depending on the size of the PMC-airplan.

D. SOCAL PROP EXAMPLE RESULTS

SOCAL PROP example output for each aircraft is in Tables 7, 8, and 9.

TAKE OFF	FROM	LAND	AT	DELAY	PAX	CARGO
08:00	ESX	08:21	NZY	30	24	0
08:51	NZY	09:12	ESX	30	24	0
09:42	ESX	10:03	NZY	30	8	0
10:33	NZY	10:45	GBY	30	10	1
11:15	GBY	11:29	BHR	30	20	0
11:59	BHR	12:13	GBY	30	12	0
12:43	GBY	12:57	BHR	30	6	0
13:27	BHR	13:37	ESX	0	0	0

Table 7. SOCAL PROP example output for aircraft 1CH53. The table has all required information for the PMC plan: routing, takeoff times, landing times, delay times, and PMC transported per leg. For example, on the first line 1CH53

takes off from ESX at 08:00, lands at 08:21 at NZY, delays on NZY for 30 minutes prior to the next takeoff, and carries 24 passengers and 0 cargo units.

TAKE OFF	FROM	LAND	AT	DELAY	PAX	CARGO
08:00	ESX	08:10	BHR	30	4	0
08:40	BHR	08:54	GBY	30	4	0
09:24	GBY	09:35	NZY	30	20	0
10:05	NZY	10:19	BHR	30	0	0
10:49	BHR	10:59	ESX	0	0	0

Table 8. SOCAL PROP example output for aircraft 2CH53.

TAKE OFF	FROM	LAND	AT	DELAY	PAX	CARGO
0805	ESX	08:16	NZY	45	24	0
0901	NZY	09:12	ESX	45	24	1
0957	ESX	10:07	NZY	45	24	0
1052	NZY	10:59	BHR	45	0	0
1144	BHR	11:49	ESX	45	0	0
1234	ESX	12:39	BHR	45	6	0
1324	BHR	13:29	ESX	0	16	0

Table 9. SOCAL PROP example output for aircraft 3V22.

Calculating the takeoff time for aircraft *h* at ICAO$^+$ *i* as the l^{th} stop ($takeoff_{l,h}$) is a post-processing step that is a function of the landing time and the associated transit time from *i* to *j* (when *j* is the l+1st stop):

$$takeoff_{l,h} = T_{l+1,h} - trans_{i,j,h} \,. \tag{20}$$

Calculating the deck delay of the l^{th} stop at ICAO$^+$ *j* ($deckdelay_{j,l}$) is a post-processing step that is a function of the takeoff and landing times of aircraft *h* at the l^{th} stop (when *j* is the l^{th} stop):

$$deckdelay_{j,l} = takeoff_{l,h} - T_{l,h} \,. \tag{21}$$

Visual inspection of the MIP output ensures all constraints are met. Table 10 verifies section constraints for 1CH53 and 2CH53 and Table 11 verifies the HOSTAC pairings.

AIRCRAFT	FROM	TO	LAND
1CH53	ESX	NZY	08:21
3V22	ESX	NZY	08:16
1CH53	NZY	ESX	09:12
3V22	NZY	ESX	09:12
1CH53	ESX	NZY	10:03
3V22	ESX	NZY	10:07

Table 10. Section constraints for SOCAL PROP example. Each section requirement is met for 1CH53. For example, on the first two lines, 1CH53 and 3V22 both take off from ESX and land at NZY at 08:21 and 08:16, respectively. All 3V22 and 1CH53 landing times are within the required five-minute difference (*maxsect* = 5).

FROM	TO
ESX	NZY
NZY	ESX
ESX	NZY
NZY	BHR
BHR	ESX
ESX	BHR
BHR	ESX

Table 11. HOSTAC pairings for SOCAL PROP example. As desired, the $ICAO^+$ to $ICAO^+$ pairings for 3V22 do not include GBY.

By inspection of Tables 3, 7, 8, and 9 we see that all aircraft and ICAO$^+$ time block constraints are satisfied.

E. PROP TRIALS

To test PROP's performance, we solve 18 trials modeled after previously developed real-world PMC-airplans. Different constraints are combined to verify compatibility. These trials have between 300 and 37,000 constraints, between 2,200 and 12,000 variables, and include up to 1,000 discrete variables. Table 12 lists the 18 trials with the associated ARG PMC planning constraints.

Trial	# ICAO$^+$	# HELOS	# PAX	# CARGO	SECTION	START	STOP	HOSTAC	HELO TIME	ICAO$^+$ BLOCK
1	2	1	200	0	0	0	0	0	0	0
2	2	2	500	60	0	0	0	0	0	0
3	2	2	50	2	1	0	0	0	0	0
4	3	3	214	1	0	1	0	0	0	0
5	3	3	350	1	0	0	1	0	0	0
6	3	3	350	1	0	0	0	1	0	0
7	2	1	500	0	0	0	0	0	1	0
8	2	1	300	0	0	0	0	0	0	1
9	4	3	308	2	0	0	0	0	1	1
10	4	3	100	0	1	0	0	1	0	0
11	4	4	100	0	1	1	0	0	0	0
12	4	4	308	2	1	0	0	0	1	0
13	4	2	94	8	1	0	1	0	0	0
14	5	3	100	2	1	0	0	0	0	1
15	4	2	238	2	1	0	0	0	1	1
16	3	2	100	5	0	1	1	1	0	0
17	4	3	308	2	0	0	0	1	1	1
18	5	4	345	30	1	1	1	1	1	1

Table 12. PROP Trials. Each successive trial increases in complexity: no constraints, one constraint, and then constraint combinations. The column headers are described in Table 13.

COLUMN HEADER	EXPLANATION
TRIAL	Trial number
# ICAO$^+$	Number of ICAOs$^+$ with PMC requests
# HELOS	Number of aircraft available for PMC
# PAX	Number of total passengers requesting transport for one day; requests are disparate across the ICAOs$^+$
# CARGO	Number of total cargo requests for one day; requests are disparate across the ICAOs$^+$
SECTION	0: no section requirement; 1: at least one aircraft requires section support for at least one i to j pairing
START	0: all aircraft start at the same ICAO$^+$; 1: one aircraft starts at a different ICAO$^+$ from the other aircraft
STOP	0: all aircraft end at the same ICAO$^+$; 1: one aircraft ends at a different ICAO$^+$ from which it started
HOSTAC	0: all aircraft can fly to every ICAO$^+$; 1: one aircraft cannot fly to one ICAO$^+$
HELO TIME	0: aircraft is/are available the entire fly day: 1: one aircraft is not available for the entire fly day
ICAO$^+$ BLOCK	0: ICAO$^+$ time blocks one and two are identical; 1: ICAO$^+$ time blocks one and two are different

Table 13. PROP trial header explanations for Table 12.

F. TRIAL RESULTS

We start by seeking an optimal solution for each of the 18 trials within 1,000 seconds. For each trial where PROP fails to converge to a guaranteed optimal solution within 1,000 seconds, we conduct an additional test where PROP terminates after one hour (i.e., 3,600 seconds) or as soon as PROP finds a solution guaranteed to be within 10% of optimal. Table 14 displays the results for each of these 18 trials.

Trial	Runtime (seconds)	Relative gap (%)	optcr (%)	reslim (seconds)
1	0.1	0.0	0.0	1,000
2	0.1	0.0	0.0	1,000
3	0.5	0.0	0.0	1,000
4	1.3	0.0	0.0	1,000
5	17.9	0.0	0.0	1,000
6	1.9	0.0	0.0	1,000
7	0.1	0.0	0.0	1,000
8	0.1	0.0	0.0	1,000
9	1,382.4	0.1	0.1	3,600
10	49.9	0.0	0.0	1,000
11	13.4	0.0	0.0	1,000
12	3,600.0	12.2	0.1	3,600
13	110.3	0.0	0.0	1,000
14	1,728.0	0.1	0.1	3,600
15	3,600.0	17.1	0.1	3,600
16	0.3	0.0	0.0	1,000
17	517.0	0.0	0.0	1,000
18	3,600.0	21.3	0.1	3,600

Table 14. PROP MIP results. The results are taken directly from GAMS (2013) output. Table headers are defined as:

Runtime: Total time in seconds to solve PROP MIP.
Relative gap: The relative gap assesses the quality of the best integer solution found with respect to a bound on the quality of any possible integer solution we have not found. The relative gap from GAMS (2013) is:

$$\frac{\text{"best integer solution"} - \text{"best estimate solution"}}{\min\left(|\text{"best estimate solution"}|, |\text{"best integer solution"}|\right)}$$

optcr: Relative optimality criterion. MIP solution stops if the relative gap drops below optcr (GAMS, 2013).
reslim: Time limit for solver in seconds. The MIP run stops if no other stopping condition is met prior to the run time reaching this limit.

From the results in Table 14, we partition the trials into two distinct test sets. Trials in Test Set 1 solve in less than two minutes with a relative gap of zero. Trials in Test Set 2 solve no faster than 517 seconds and do not reach a

relative gap of zero, except for Trial 17. Trials 12, 15, and 18 reach the one-hour time limit prior to reaching a relative gap of 10%. We show Test Set 1 in Table 15 and Test Set 2 in Table 16.

Trial	Constraint(s)	Runtime (seconds)	Relative gap (%)
1	none	0.1	0.0
2	none	0.1	0.0
3	SECTION	0.5	0.0
4	START	25.1	0.0
5	STOP	17.9	0.0
6	HOSTAC	1.9	0.0
7	HELO TIME	0.1	0.0
8	ICAO+ BLOCK	0.1	0.0
10	SECTION, HOSTAC	49.9	0.0
11	SECTION, START	13.4	0.0
13	SECTION, STOP	94.7	0.0
16	START, STOP, HOSTAC	0.3	0.0

Table 15. Test Set 1. Each trial is listed with the associated constraint(s). For example, Trial 10 includes a section constraint and a HOSTAC constraint.

Trial	Constraint(s)	Runtime (seconds)	Relative gap (%)
9	HELO TIME, ICAO+ BLOCK	1,382.4	10.0
12	SECTION, HELO TIME	3,600.0	12.2
14	SECTION, ICAO+ BLOCK	1,728.0	10.0
15	SECTION, HELO TIME, ICAO+ BLOCK	3,600.0	17.1
17	HOSTAC, HELO TIME, ICAO+ BLOCK	517.0	0.0
18	SECTION, START, STOP, HOSTAC, HELO TIME, ICAO+ BLOCK	3,600.0	21.3

Table 16. Test Set 2. Each trial requires at least 517 seconds to solve. Note that each trial in Test Set 2 includes the “HELO TIME” and/or “ICAO+ BLOCK” constraint(s). Trials 12, 15, and 18 reach a one-hour time limit before guaranteeing a solution within 10% of optimal.

Table 15 shows that if only one ARG PMC planning constraint is required, PROP solves the MIP quickly. Also, combining constraints that do not include "HELO TIME" or "ICAO$^+$ BLOCK", does not substantially increase the run times as seen in Trials 10, 11, 13, and 16. Runtime does increase up to one hour when including the "HELO TIME" or "ICAO$^+$ BLOCK" constraint with at least one other ARG PMC planning constraint (Test Set 2). This is a significant improvement over the current PMC-airplan development time that otherwise may take up to 12 hours to complete. Common, real-world PMC-airplans most closely resemble the trials in Test Set 1. PROP reduces planning time for Test Set 1 PMC-airplans from about one hour to mere seconds.

IV. CONCLUSIONS AND OPPORTUNITIES

A. SUMMARY

Currently, PMC coordinators develop each PMC-airplan manually. Experience shows there is no thorough search of all available routes and little consideration is placed on the cost-effective employment of the aircraft. PROP includes two-parts: (1) a graphical user interface that aids PMC-airplan data input and communicates to solution software and (2) a mixed-integer program that generates PMC-airplan solutions. For typical PMC-airplans that currently take about one hour to create manually, PROP generates optimized PMC-airplans in seconds. For atypical PMC-airplans that currently may take up to 12 hours to manually complete, PROP generates optimized PMC-airplans in an hour or less.

B. FUTURE DEVELOPMENT

GAMS (2013) is yet to be broadly authorized for use on Navy networks. The next step to gain wide acceptance of PROP is to develop a heuristic that is compatible with secret U.S. Navy computer networks and that is not reliant on commercial optimization software. Such a heuristic would allow for wide-scale acceptance of PROP in ARGs. This thesis provides the modeling that will allow one to compare the heuristic to the optimal PROP solutions and determine the heuristic's level of performance.

We suggest the following PROP improvements:

1) PMC coordinator-controls in the interface to allow manual adjustment of DOW calculations. For legs meeting the section requirements, an enhanced version of PROP would allow the user to verify section requirement validity.

2) PROP output should include a by-name manifest. Currently, PROP identifies PMC movements by the total number of passengers moved

per leg. PROP should identify passenger movements by name so as to eliminate the need to sort through the PROP manifest sheet.

3) Surface PMC. Small surface vessels launched from ARG ships also transport PMC and have similar considerations as PMC aircraft. Including surface PMC movements in PROP would integrate all PMC movements which are currently managed manually.

One may also expand PROP to consider operational and training flight planning. Including all aircraft mission-types would provide a planning system to optimally and efficiently develop routes for the entire airplan.

The desired end state for PROP is a program that can process PMC requests, track request approval, plan the PMC flights, and notify requestors of PMC flight times. Such a single-source program would seamlessly connect all aspects of PMC planning from beginning to end.

LIST OF REFERENCES

Damren, P. L. 2010. Standard operating procedures for flight operations. 31st Marine Expeditionary Unit, Okinawa, Japan.

Brown, G. G., Carlyle, W. M., Dell, R. F., Brau J. W. 2013. Optimizing intratheater military airlift in Iraq and Afghanistan. *Military Operations Research* **18** 35-52.

Drexl, M. (2012). Synchronization in vehicle routing - A survey of VRPs with multiple synchronization constraints. *Transportation Science* **46** 297-316.

GAMS Development Corporation. 2013. General Algebraic Modeling System (GAMS) Release 24.2.1, Washington, D.C.

Military-Today.com. (n.d.). V-22 Osprey images. Retrieved September 02, 2015, http://www.military-today.com/helicopters/bellboeing_v_22_osprey_images.htm

Moreno, L., Aragao, M. P., Uchoa, E. 2006. Column generation based heuristic for a helicopter routing problem. Àlvarez C, Serna M, eds. *Proc. 2006 5th International Workshop, WEA* (Springer-Verlag, Berlin, Germany), 219-231.

North Atlantic Treaty Organization. 2013. APP 2(F)/MPP 2(F): Helicopter operations from ships other than aircraft carriers. NATO Standardization Agreement(STANAG), Brussels, Belgium.

Qian, F., Gribkovskaia, I., Halskau, Ø. 2011. Helicopter routing in the Norwegian oil industry: Including safety concerns for passenger transport. *International Journal of Physical Distribution & Logistics Management* **41** 401-415.

Source: "Southern California". 2013. 32° 37' 43"N 117° 09' 46"W. Retrieved August 31, 2015, from Google Earth.

Timlin, M. T., Pulleyblank W. R. 1992. Precedence constrained couting and helicopter scheduling: Heuristic design. *Interfaces* **22** 100-111.

U.S. Marine Corps. 2009. Bataan Amphibious Ready Group. Retrieved September 3, 2015, https://commons.wikimedia.org/wiki/File:US_Navy_090521-M-8752R-174_he_Bataan_Amphibious_Ready_Group_(ARG)_is_underway_in_formation_in_the_Atlantic_Ocean.jpg

U.S. Navy. 2015a. 31st MEU Marines board MH-60s Seahawk. Retrieved September 03, 2015, https://www.dvidshub.net/image/1809847/31st-meu-marines-board-mh-60s-seahawk#.VesvR-Ih22x

U.S. Navy. 2015b. USS Fort McHenry flight operations. Retrieved September 02, 2015, https://www.dvidshub.net/image/2020015/uss-fort-mchenry-flight-operations#.VetAHOlh22w

Wray, J. 2009. Optimizing helicopter assault support in a high demand environment. Master's thesis, Naval Postgraduate School, Monterey, California.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California